MODELING AND DYNAMICAL SIMULATION OF VIBRATION-DRIVEN ROBOTS

Felix Becker[1], Vladimir Minchenya[2], Igor Zeidis[1], Klaus Zimmermann[1]

[1] Ilmenau University of Technology, Department of Technical Mechanics
[2] Belarusian National Technical University Minsk, Department of Instrument-making

ABSTRACT

In this paper piezo-driven micro robots are introduced for 2-dimensional locomotion on a flat solid surface. To find important locomotion effects an experimental setup using a scanning electron microscope is presented. The results are given and the principles of motion are described. The working principle of this type of robots deploys forced vibrations of continua. The non-classical legs are excited by the actuator with frequencies in range of 1 – 100 kHz, which leads to complex trajectories at the endpoints of the legs. The behavior of the actuator is studied in detail using analytical models based on Kirchhoff hypothesis of plates and laminates, as well as computational models. The results are compared with experimental investigations.

Index Terms – micro robot, piezo actuator, vibration of continua, theory of plates

1. INTRODUCTION

The authors are currently developing small micro robots for the movement in two dimensions on a flat ground based on vibrated systems. Forced vibration of continua, especially bending vibrations of beams and plates are used to develop a moveable system. This motion principle, called elastodynamic locomotion, is especially useful for the creation of micro robots, which are driven by piezoelectric actuators. These actuators are working with high energy efficiency and in a high frequency range. The objective is to create systems, which are controllable with only one actuator, following the principle “intelligence in the mechanics” [1]. Based on piezoelectric bending actuators several prototypes of micro robots are developed. Three of these robots are presented in the following figures. The structural specifications are given in Table 1.

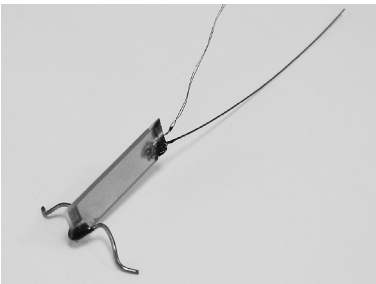

Figure 1: Minch-Robot

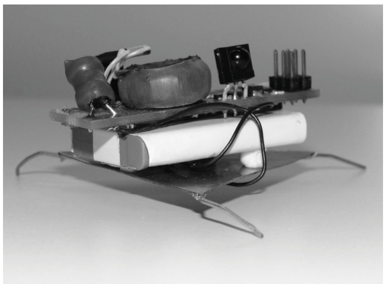

Figure 2: Beetle-Robot

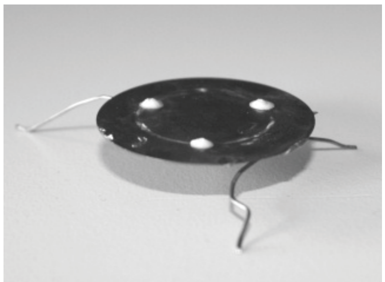

Figure 3: Plate-Robot

Minch-Robot (high-speed robot) and Beetle-Robot (programmable and remote controlled robot) are described in [2], [3] and [4] in detail. In this paper, the robot presented in Figure 3, called Plate-Robot, will be discussed in detail. This type of robots has a very light weight, is ease to be controlled and operates with a high velocity.

A similar approach was followed by several scientific projects in different environments. A wireless piezoelectric micro robot could be found in [5]. For the movement on the water surface, a water strider robot is presented in [6]. Other examples of biologically inspired robots, using piezoelectric bending actuators, are presented in [7] (inchworm locomotion device), [8] (flying robot), [9] (swimming robot) and [10] (robots with swarm application).

©2011- TU Ilmenau

Table 1: Structural specifications of the robots

	Minch-Robot	Beetle-Robot	Plate-Robot
Length x Width x Height	45 x 15 x 10 mm³	69 x 80 x 30 mm³	58 x 42 x 10 mm³
Mass	1.7 g	31.7 g	3.5 g
Max. velocity	540 mm/s (on aluminum)	20 mm/s (on glass)	150 mm/s (on glass)
Actuator	Rectangular piezo bimorph	Circular piezo unimorph	Circular piezo unimorph
Excitation frequency	1 – 45 kHz	12 – 70 kHz	10 – 60 kHz

2. DESIGN OF PLATE-ROBOT

A piezoelectric unimorph actuator is both the base body and the actuation element of Plate-Robot (Figure 3). This circular laminate is formed by a passive metal plate with a diameter of 35 mm. A piezo ceramic layer is bonded on it with a diameter of 25 mm. The actuator is controlled through a sinusoidal electrical signal with amplitude of 20 V. The three contact points to the solid ground are realized by three metal legs, which are soldered on the base body. It should be remarked, that these “legs” are not active moveable legs in a biological context but vibration transducers.

3. PRINCIPLE OF MOTION OF PLATE-ROBOT

To analyze the principle of motion of the presented robots, experiments are made using a scanning electron microscope (SEM). The experimental setup (Figure 4) consists of a piezo electric plate with soldered legs. In Figure 5, the overlay of two photos is presented. The solid scheme represents the endpoint of a leg in a static state. The moveable part shows the systems under excitation. It should be noticed, that with the used microscope, it is possible to take one picture every three seconds. The vibration frequency of the leg is much higher, which means that the marked amplitudes do not represent necessarily the maximum value. The leg is excited by the bending vibrations of the actuator plate. According to the frequency different vibration forms are produced. The endpoints of the legs perform longitudinal and transversal vibrations. The trajectory corresponds to the relation between the amplitude of the longitudinal and transversal vibrations (Figure 5). The motion of the robot depends on this vibration behavior. During the movement the friction forces in the contact points between robot and environment are changed periodically. The motion direction could be controlled using the resonance shift between the legs. This resonance shift is caused by the asymmetric system properties. Furthermore the robot legs lose the contact to the surface during the vibration. The motion is influenced by the resulting shock effects.

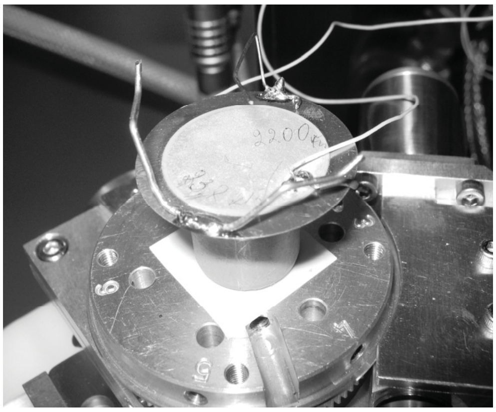

Figure 4: Experimental setup in SEM

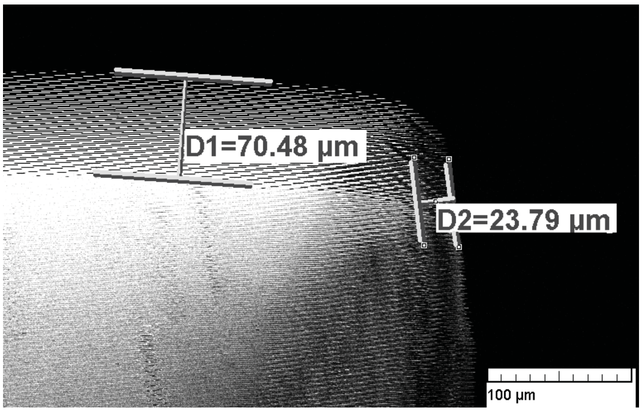

Figure 5: SEM picture of a vibrating leg

4. MODELLING, SIMULATION AND EXPERIMENTS OF THE ACTUATOR

4.1. Analytical description of actuator dynamics

The actuation system is modeled as a thin elastic plate, which can be described with the help of the Kirchhoff hypothesis of plates and laminates. A characteristic parameter of a plate is the bending stiffness N. For the introduction of this parameter and the use of the Kirchhoff hypothesis a neutral area is needed. In a homogenous plate this strain- and stress-free area is situated exactly in the middle. The position changes in a laminated plate. This is illustrated in Figure 6, where $\vec{e}_z$ and $\vec{e}_r$ are the unit vectors, E_1 and E_2 the Young’s modulus of the materials, h_1 and h_2 the thickness of the plates and h_n the distance between the adherend and the neutral area. It is assumed that there is no motion between the adherend surfaces. Furthermore the distributions of strain $\varepsilon(z)$ and stress $\sigma(z)$ are presented. In equation (4.1) and (4.2) the calculation of the bending stiffness of a homogenous plate as well as a laminate is shown, where υ is Poisson's ratio [11].

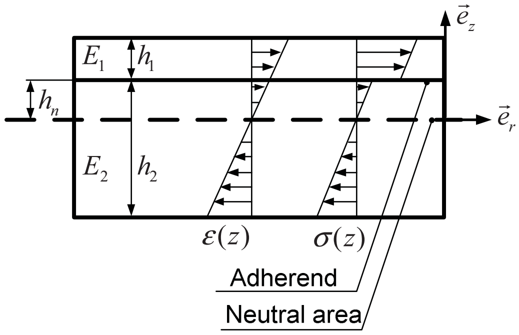

Figure 6: Stress and strain in a two layer laminate

$$N_{\mathrm{hom}ogenous} = \frac{Eh^3}{12(1-\upsilon^2)} \tag{4.1}$$

$$N_{La\min ate} = \frac{E_1 h_1{}^3}{12(1-\upsilon^2)} \cdot \frac{ae(1+a)^2 + (1-ea^2)^2}{1+ae} \tag{4.2}$$

$$a = \frac{h_2}{h_1} \tag{4.3}$$

$$c = \frac{E_2}{E_1} \tag{4.4}$$

The equations for the bending vibration of a circular plate and the general solution are written in (4.5) and (4.6), where ρ is the density, ω the natural angular frequency, λ the eigenvalue, J and I the Bessel function and the modified Bessel function of first kind. The problem is considered to be rotational symmetric so that the function, which is describing the bending of the plate w, depends only on the radius r and the time t.

$$\Delta\Delta w(r,t) + \frac{\rho h}{N}\partial_{tt}^2 w(r,t) = 0 \tag{4.5}$$

$$w(r,t) = \left[c_1\cos(\omega t) + c_2\sin(\omega t)\right]\cdot\left[c_3 J_0(\lambda r) + c_4 I_0(\lambda r)\right] \tag{4.6}$$

The influence of the elastic robot legs to the actuator plate is modeled as linear springs (Figure 7). We assume that the stiffness of the plate along the circumference is relatively high so that the springs can be modeled as evenly distributed over the circumference of the plate (Figure 8).

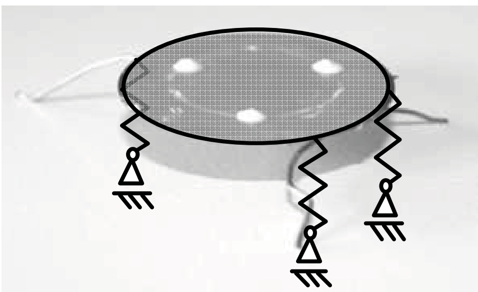
Figure 7: Boundary conditions of the actuator of Plate-Robot

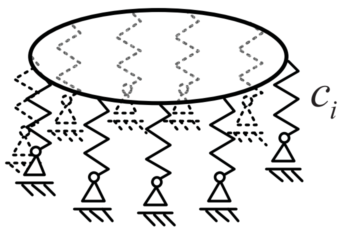

Figure 8: Boundary conditions of the analytical model

The boundary conditions are presented in (4.7), where Q_r is the shear force, M_r the bending moment and $\overline{c}$ a characteristic stiffness, which can be calculated using (4.8).

$$\begin{aligned} 0 &= Q_r(R,t) + \overline{c}w(R,t) \\ 0 &= M_r(R,t) \end{aligned} \tag{4.7}$$

$$\overline{c} = \frac{\sum_i c_i}{2\pi R} \tag{4.8}$$

The characteristic equation, to calculate the eigenvalues and natural frequencies of a such plate, is formulated in (4.9) where F_1, F_2 and F_3 are functions of the material and geometrical properties, as well as of the modified Bessel function of the first kind and different orders. The parameter c could be calculated as $c = \overline{c}R^3/N$ and is the relation between characteristic stiffness parameters. For different boundary conditions, on the circumference of the plate, i.e. fixed or flexible support, the eigenvalues could be found in the literature [12] and [13]. They are used to verify the analytical model as well as the FEM model. Some results of the numerical analysis of equation (4.9) are presented in Table 2.

$$0 = F_1(c,\upsilon,\lambda R)\cdot J_0(\lambda R) + F_2(c,\upsilon,\lambda R)\cdot J_1(\lambda R) + F_3(c,\upsilon,\lambda R)\cdot J_2(\lambda R) \quad (4.9)$$

4.2. FEM modeling and simulation

To analyze to vibration behavior of the actuator, under the described boundary conditions, a FEM model is formulated. The plate is modeled to be homogenous. With the help of a modal analysis, the natural frequencies and normal modes are simulated and compared with the results from the analytical calculations. It could be noticed that the results of both modeling methods are agree. With the full rotationally symmetric mathematical modeling can be calculated only the natural frequencies of such normal modes. With FEM simulation also the non-symmetric modes are determined. Some examples are given in Figure 9 to 12.

Table 2: Natural frequencies [Hz] for the rotational symmetric normal modes of a plate under linear elastic boundary conditions for one set of parameters - analytical and FEM calculations

No.	1	2	3	4	5	6
Analytical	179	798	2062	4495	7957	12415
FEM	216	782	2012	4430	7903	12432

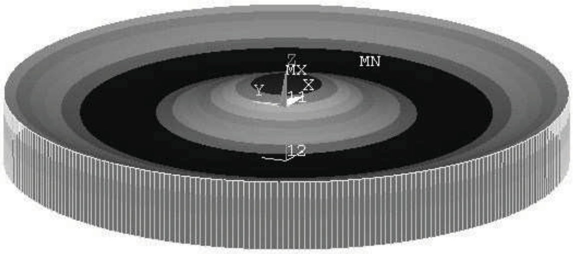

Figure 9: 3rd rotational symmetrical normal mode (2012 Hz)

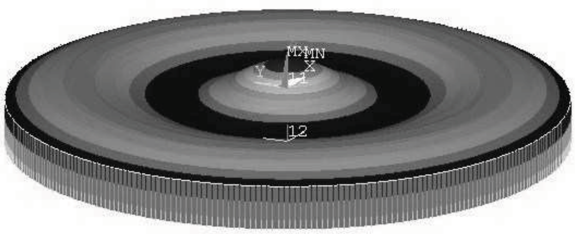

Figure 10: 4th rotational symmetrical normal mode (4430 Hz)

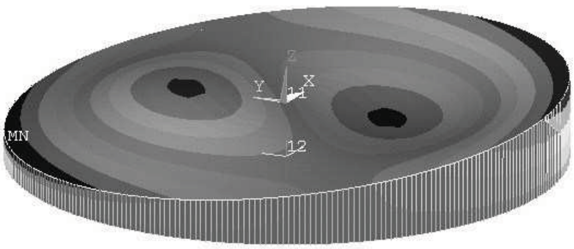

Figure 11: 9th normal mode (1206 Hz)

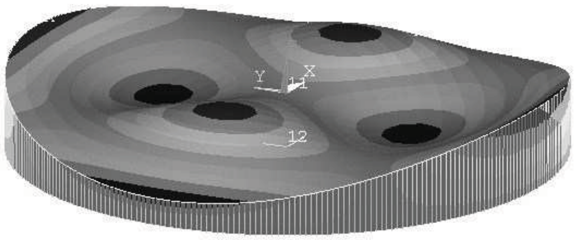

Figure 12: 32nd normal mode (4430 Hz)

4.3. Experiments

The natural modes of a circular piezo unimorph actuator are investigated and presented in Figure 13. In agreement with the analytical and computational models, it is possible to establish different normal modes. The boundary conditions of this plate are different than the presented models. Also the soldered dots have an influence to the vibration behavior.

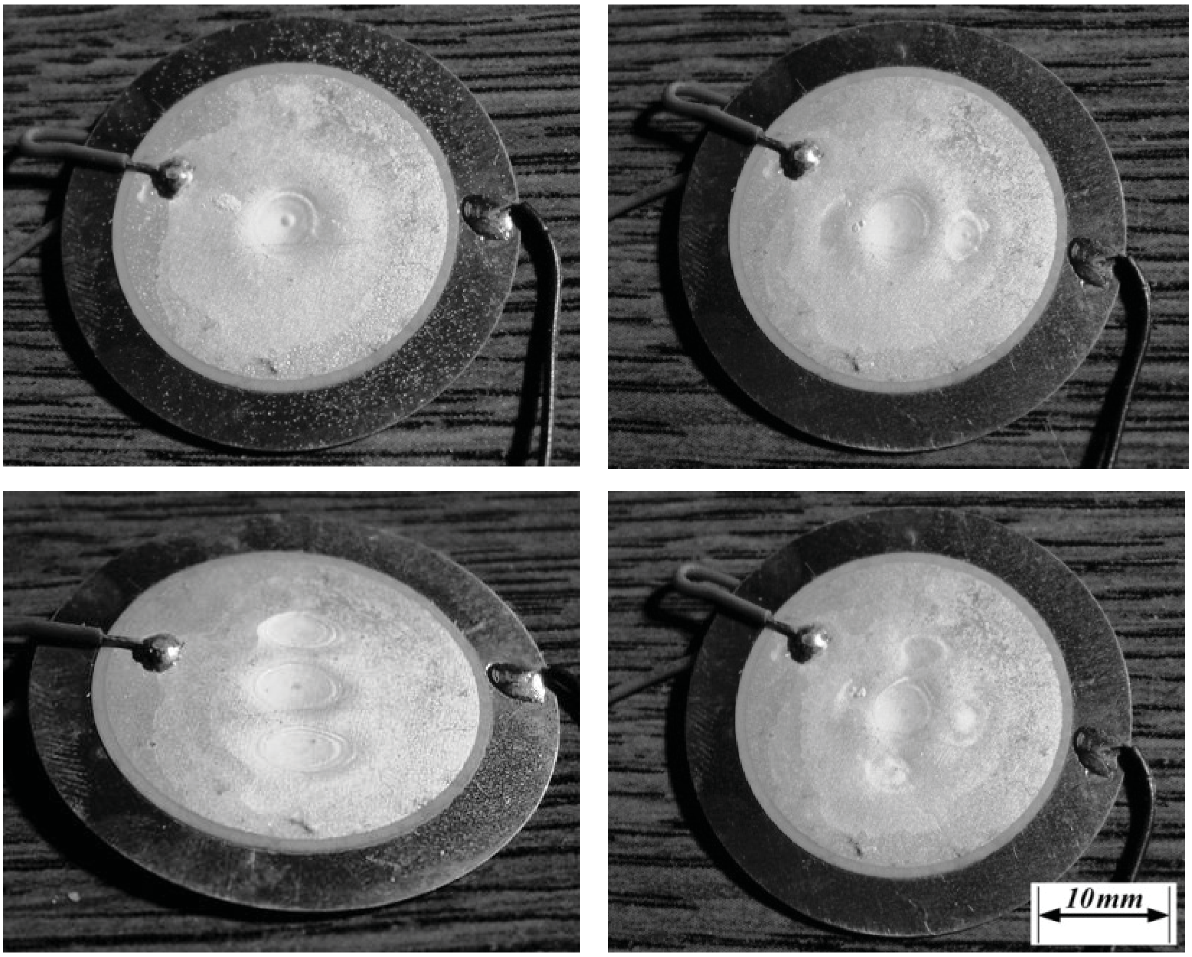

Figure 13: Natural modes of the actuator of the robot

5. CONCLUTIONS AND OUTLOOK

The presented micro robots can be classified as low cost locomotion systems. The author's idea is to explore the mechanical properties of a beam or a plate to develop locomotion systems, which can be controlled by only one parameter (the actuation frequency). Knowing the resonance characteristics (natural frequencies and normal modes) of vibrating continua, the motion is generated of the mobile robots on a flat surface. In this article, analytical and computational models are given to determine how the actuator is influenced by the robot design and what kinematic conditions are exciting the legs. The models have been analyzed by simulations and compared with experimental results.

Further investigations will be connected with robot's legs, which are acting as vibration transducers. Including the boundary conditions, given by the contact characteristic between robot and environment, will be determined the resonance characteristics. The objective of the future work is to find the qualitative and quantitative relations between the excitation frequency and the locomotion properties. Models with a lower grad of abstraction are needed. Further micro robots, which are in the design process, will use the described principle of motion. The concentration on the motion of the mobile robots in the different environments will arise in the further work.

6. ACKNOWLEDGMENTS

The work has been supported by the German Research Foundation (DFG) under grant Zi 540/11-1 as well as by the Free State of Thuringia via graduation scholarship.

7. REFERENCES

[1] R. Blickhan, A. Seyfarth, H. Geyer, S. Grimmer, H. Wagner and M. Günther, “Intelligence by Mechanics,” Philosophical Transactions of the Royal Society 365, London, United Kingdom, pp. 199-200, 2007.

[2] F. Becker, V. Minchenya, K. Zimmermann and I. Zeidis, “Single Piezo Actuator Driven Micro Robots for 2-dimensional Locomotion,” Electron. Proceedings of Workshop on Microactuators and Micromechanisms, Aachen, Germany, 2010.

[3] K. Zimmermann, I. Zeidis, V. Böhm, F. Becker and V. Minchenya, “An Approach to the Mechanics of Non-pedal Locomotion Systems Using Analytical and Computational Methods,” Problems of Mechanics No.4 (41), IFToMM, Tbilisi, Georgia, pp. 5-14, 2010.

[4] K. Abaza, “Ein Beitrag zur Anwendung der Theorie undulatorischer Lokomotion auf mobile Roboter,” Dissertation at Ilmenau University of Technology, Universitätsverlag, Ilmenau, Germany, 2007.

[5] C. H. Pan, S. S. Tzou, R. Y. Shiu, “A Novel Wireless and Mobile Piezoelectric Micro Robot,” Proceedings of the IEEE International Conference on Mechatronics and Automation, IEEE, Xi’an, China, 2010.

[6] S. Y. Song and M. Sitti, “Surface-Tension-Driven Biologically Inspired Water Strider Robot: Theory and Experiments,” Transactions on Robotics 23 No. 3, IEEE Robotics and Automation Society, pp.578-589, 2007.

[7] N. Lobontiu, M. Goldfarb and E. Garcia, “A Piezoelectric-driven Inchworm Locomotion Device,” Mechanism and Machine Theory 36, Elsevier Science Ltd., pp. 425-443, 2001.

[8] R. J. Wood, “The First Tabkeoff of a Biologically Inspired At-Scale Robotic Insect,” Transactions on Robotics 24 No. 2, IEEE Robotics and Automation Society, pp. 341-347, 2008.

[9] G. Kosé, M. Shoham and M. Zaaroor, “Propulsion Method for Swimming Microrobots,” Transactions on Robotics 23 No. 1, IEEE Robotics and Automation Society, pp. 137-150, 2007.

[10] P. Valdastri, P. Corradi, A. Menciassi, T. Schmickl, K. Crailsheim, J. Seyfried and P. Dario, "Micromanipulation, Communication, Swarm Intelligence Issues in a Swarm Microrobotic Platform," Robotics and Autonomous Systems, 54, pp. 789-804, 2006.

[11] T. Rogge, “Entwicklung eines piezogetriebenen Mikroventils – von der Idee bis zur Vorserienfertigung,” Dissertation at the University of Karlsruhe, Forschungszentrum Karlsruhe GmbH, Germany, 2001.

[12] I. Szabó, “Höhere technische Mechanik: nach Vorlesungen,” 4. Aufl., Springer, Berlin, Germany, 1964.

[13] D. Gross, W. Hauger and P. Wriggers, “Technische Mechanik 4 – Hydromechanik, Elemente der Höheren Mechanik, numerische Methoden,” 6. Aufl., Springer, Berlin, Germany, 2007.